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Non-Homogeneous Layered Fiber Reinforced Concrete

Vitalijs Lusis, Andrejs Krasnikovs

***Abstract*—**Fiber reinforced concrete is important material for load bearing structural elements. Usually fibers are homogeneously distributed in a concrete body having arbitrary spatial orientations. At the same time, in many situations, fiber concrete with oriented fibers is more optimal. Is obvious, that is possible to create constructions with oriented short fibers in them, in different ways. Present research is devoted to one of such approaches- fiber reinforced concrete prisms having dimensions 100mm ×100mm ×400mm with layers of non-homogeneously distributed fibers inside them were fabricated.

Simultaneously prisms with homogeneously dispersed fibers were produced for reference as well. Prisms were tested under four point bending conditions. During the tests vertical deflection at the center of every prism and crack opening were measured (using linear displacements transducers in real timescale). Prediction results were discussed.

***Keywords*—**Fiber reinforced concrete, 4-point bending, steel fiber.

I. Introduction

CONCRETES with high strength can be produced using traditional materials, micro admixtures, and applying conventional mix design methods including postcasting treatment [1]–[3].

The main problem of the high strength concrete is its increasing brittleness while its strength is being increased. The higher the strength of the concrete, the lower is its ductility. This inverse relation between strength and ductility is a serious drawback when is planning to use the high strength concrete in practice. A compromise between these two conflicting properties of the concrete can be obtained by adding short fibres [4].

Fibers are usually used in concrete to control cracking due to drying and autogenous shrinkage. Nowadays is possible to note a rapid growth in the use of steel fibres in a concrete, such way obtaining Steel Fibre Reinforced Concrete (SFRC). Sometimes, steel fibers are substituting the steel bars in conventional concrete in another situation is possible to combine them in concrete structures. There are the substantial differences in the physical and mechanical properties between SFRC and classical concrete, the use of SFRC is still a challenge for modern engineers. Usually is recognized that the mechanical, cracking and fracture, properties of SFRC are far superior comparing to the classical concrete. The addition of fibers into the concrete matrix counteracts its brittleness, producing materials with increased tensile performance, toughness and improved ductility [5], [6]. Ductility in SFRC is observed as bulk property. Physical nature of such ductility is damage accumulation, where cracks are bridging by fibers and fibers are triggering each crack growth and opening.

As the fibre volume content increases, the compressive [7]–[9] (less), and the tensile (more) post-peak behavior improves as well as a greater fracture energy can be observed [10].

Use of SFRC is continuously increasing; however its potentials are limited due to the lack of universally accepted and reliable calculations guidelines. To optimize the performance of SFRC in structural members it is necessary to establish its mechanical properties precisely.

Important problem for fiber concrete is fibers orientation in the sample. Some sources say, the structure created by the oriented fibers which are placed upon the stress distribution with uniform concentration throughout the sample volume is not recommended for the site conditions.

Presently, SFRC is primarily being used in applications where the placement of reinforcing bars is difficult, such as in hydraulic structures (dams, spillways), large industrial slabs, tunnel linings [11], [12] and in bridge decks [13].

The aim of the present research is to create and to investigate a fiberconcrete construction with non-homogeneous fibers distribution in it.

A. Physical Properties Steel Fibers

The aim of the conducted research was a study on the fiber dosage on the post-cracking behavior of steel fiber reinforced concrete.

Steel fibers have a relatively high strength and modulus of elasticity, they are protected from corrosion by the alkaline environment of the cementitious matrix, and their bond to the matrix can be enhanced by mechanical anchorage or surface roughness [14].

Steel fiber remains the most used fiber of all (50% of total tonnage used) followed by polypropylene (20%), glass (5%) and other fibers (25%) [15].

Bond between concrete matrix and fiber is dependent on the aspect ratio of the fiber.

Commercially available steel fibers were used in experiments:

The end hooked RC 80/30 BP-type steel fibers. Round, straight steel fibers are produced by cutting or chopping wire, had a length of 30mm, diameter 0.38mm, aspect ratio l/d= 79, elastic modulus 200 GPa [16].

II. Experimental Investigation

A. Samples Design

In the framework of these research beams of non-

V. Lusis is with the Faculty of Civil Engineering, Institute of Building Production and Concrete Mechanics Laboratory, Riga Technical University, Azenes Str.16/20, Riga, LV 1048 Latvia (e-mail: vitalijs.lusis@rtu.lv).

A. Krasnikovs is with the Institute of Mechanical Engineering and Concrete Mechanics Laboratory(www.bml.rtu.lv), Riga Technical University, Ezermalas Str.6k Riga, LV 1006 Latvia (phone: +371 29436518; e-mail: krasnikovs.andrejs@gmail.com).

homogeneous fiber reinforced concrete with a cross-section of 100 mm^2 × 100 mm^2 and a length was 400 mm were designed.

Fibers were added to the mix during the concrete mixing process and moulds were filled by such fiber reinforced concrete for specimens representing Group 1. For the specimens from Groups 2-6, moulds were gradually filled with the concrete mix according to the description of each group. Then fibers were uniformly scattered on the concrete surface in the mould and were pressed into concrete. During fabrication fibers were pressed by a steel grid into the concrete in the full length of the prism according to the technology described in the Riga Technical University Latvian invention patent No. 14257 [17].

Ten identical prisms of each type of non-homogeneous fiber reinforced concrete were prepared.

TABLE I
CONCENTRATIONS OF FIBERS IN THE LAYERS OF SPECIMEN (FROM THE BOTTOM TO THE TOP)

Group Nr.	Sample properties
Group Nr.1	Fiber reinforced concrete classical method. Fibers concentration 60 kg/m^3 were added to the concrete mix. Steel fibers are assumed to be dispersed with random locations and orientations in the matrix (modeling suppose that fibers are homogeneously distributed in each specimen volume homogeneously). Specimen height 100 mm.
Group Nr.2	1. Concrete layer with thickness 25 mm fiber reinforced concrete. Fiber concentration in the concrete layer 160 kg/m^3; 2. Concrete layer with thickness 25 mm fiber reinforced concrete. Fiber concentration in the concrete layer 80 kg/m^3; 3. 50 mm of concrete without fibers.
Group Nr.3	1. Concrete layer with thickness 25 mm fiber reinforced concrete. Fiber concentration in the concrete layer 160 kg/m^3; 2. 50 mm of concrete without fibers; 3. Concrete layer with thickness 25 mm fiber reinforced concrete. Fiber concentration in the concrete layer 80 kg/m^3.
Group Nr.4	1. Concrete layer with thickness 25 mm fiber reinforced concrete. Fiber concentration in the concrete layer 240 kg/m^3; 2. 75mm of concrete without fibers.
Group Nr.5	1. Concrete layer with thickness 25 mm fiber reinforced concrete. Fiber concentration in the concrete layer 160 kg/m^3; 2. 25 mm of concrete without fibers; 3. Concrete layer with thickness 25 mm fiber reinforced concrete. Fiber concentration in the concrete layer 80 kg/m^3; 4. 25 mm of concrete without fibers.
Group Nr.6	1. Concrete layer with thickness 25 mm fiber reinforced concrete. Fiber concentration in the concrete layer 160 kg/m^3; 2. 25 mm of concrete without fibers; 3. Concrete layer with thickness 25 mm fiber reinforced concrete. Fiber concentration in the concrete layer 80 kg/m^3; 4. 25 mm of concrete without fibers.

Group 1 fibers were used and randomly distributed in concrete mixture. These prisms were used as reference. As seen in Table I, while the total amount of fibers is identical for six groups of specimens and it is 60 kg/m^3, the difference only is in their distribution. For specimens of Groups 2, 3, 4, 5 and 6, fibers are distributed in different layers with various concentrations in layers. These specimens can be defined as non-homogeneous layered fiber reinforced concrete.

Standard compressive cube tests using 100 mm × 100 mm × 100 mm cube were conducted to determine the mean values of the concrete compressive strength. Average compression strength after 28 days. Strength of fiber reinforced concrete according to the test results was corresponded to class C70/85[18].

III. SETUP AND INSTRUMENTATION

A. 4-Point Bending Tests

Uniaxial tensile tests exist [19], execution is considered rather difficult. No standard test exists to determine the stress-strain curve of fiber reinforced concrete in direct tension. The observed curve depends on the size of the specimen, method of testing, stiffness of the testing machine, gage length, and whether single or multiple cracking occurs within the gage length used. For practical reasons, it is generally preferred to use bending tests. The most common test procedure is 4-point bending tests on beam specimens at an age of 28 days [20]–[22].

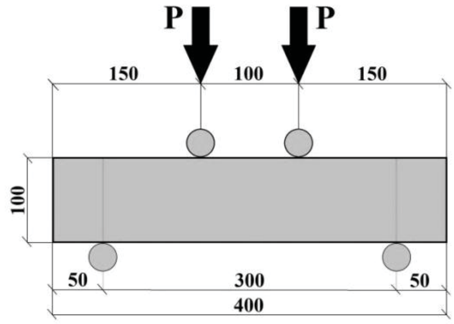

Fig. 1 Load bearing chart for the fiber reinforced concrete beam

The tests were run under controlled displacement up to a total midspan deflection equal to 10 mm. The setup scheme is shown in Fig. 1.

The loading was applied monotonically in small increments, while the loads, deflections and strains were recorded at each increment. The midspan deflection and support settlements were measured with linear voltage differential transformers (LVDTs).

B. Experimental Force–Deflection Diagrams

Force–deflection curves of the 4-point bending tests are given in Fig. 2 for one type homogeneous prisms Group 1 and 5 types of non-homogeneous prisms, respectively Group 2-6.

Each curve in Figs. 2-4 was obtained averaging testing results for ten specimens. Three stages are seen in each curve; first of them is linear elastic (deflection from 0 to 0.01 mm). In this stage the fiber reinforced concrete prisms become deformed without visible crack opening.

Fibers in the concrete do not bear significant load. The next stage begins with deviation of curves from the straight line and terminates reaching the maximum value on curve with deflection of prisms equal to 0.75 mm – 1 mm.

The large amount of fibers leads to stress concentration and overload of the concrete matrix which leads to spalling of the concrete.

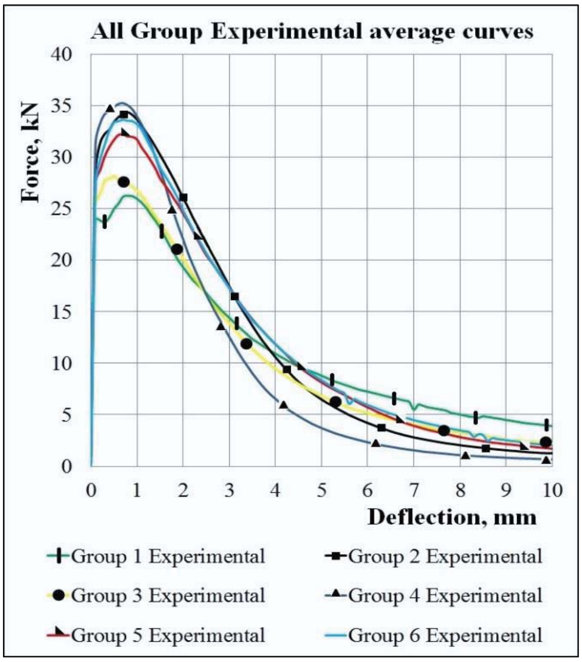

Fig. 2 Load - vertical deflection experimental graphs for specimens

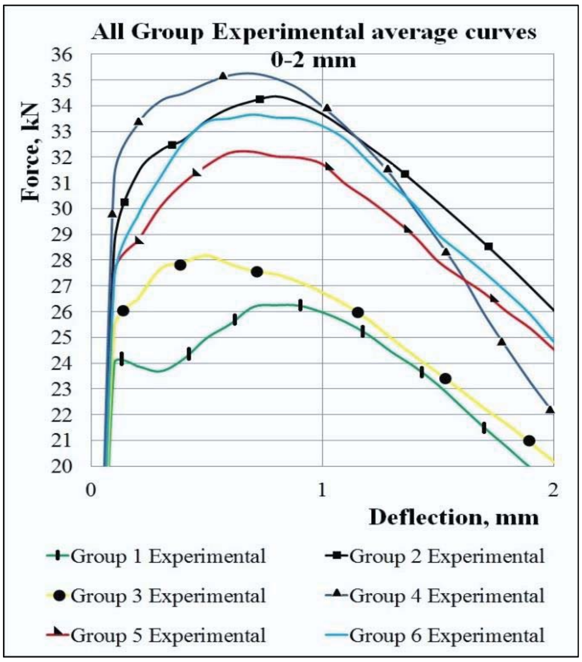

Fig. 3 Load - vertical deflection experimental graphs for specimens

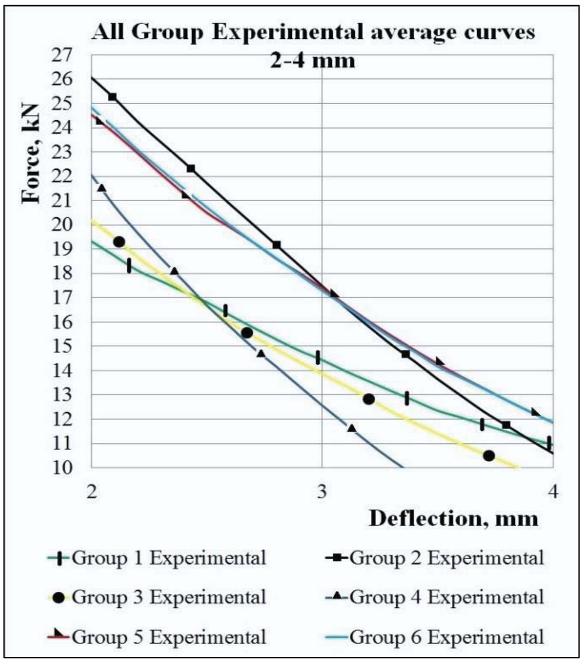

Fig. 4 Load - vertical deflection experimental graphs for specimens

In this stage concrete micro cracks accumulate and grow forming a macro crack network. The macro cracks are formed perpendicularly to the longitudinal axis of prism. The density of the macro crack network depends on the specimen's geometry, size of fibers and their amount. Fibers traversing the macro cracks begin to bear load, while the cracks are still invisible on the outer surface of specimen.

The crack with the lowest load carrying capacity (the one with the lower amount of fibers traversing it or fibers located and oriented in a less optimal way) starts to open. It proceeds the following way: fibers bearing load detach from the concrete and start pulling out from one or both ends. The individual load carrying capacity of fiber depends on its orientation towards the crack plane and how far it is extracted.

Experimental observation of fiber pull-out micromechanics [23] showed that the maximum load carrying capacity of fiber depends on the orientation of fiber towards the direction of extraction force and how much the fiber has been extracted.

The third stage is characterized by the decline of the total load carrying capacity of fiber. The capacity decreases proportionally to the size of the crack opening. Load bearing - vertical deflection at the center of prism for the specimens are given in Figs. 2-4.

It can be observed, that Group 4 reaches the highest load carrying capacity during the crack opening stage due to the highest concentration of fibers compared to other groups in the lower part of the prism which bears the maximum tensile load see Fig. 3. It can be observed, Group 1 (reference specimens) reaches a lower average load carrying capacity in the third stage (macro cracks) compared to the specimens with the non-homogeneous distribution of fibers. Certain similar tendencies can be observed among the diagrams of the average results of the specimens – the maximal load carrying capacity is reached with deflection of prisms 0.75 mm - 1 mm, which correlates with the crack opening size.

IV. Numerical Modeling

Modeling of fiber reinforced concrete cracking was performed using a previously developed numerical model [24]–[26]. Concentrations of fibers in the layers of specimen are given in Table I.

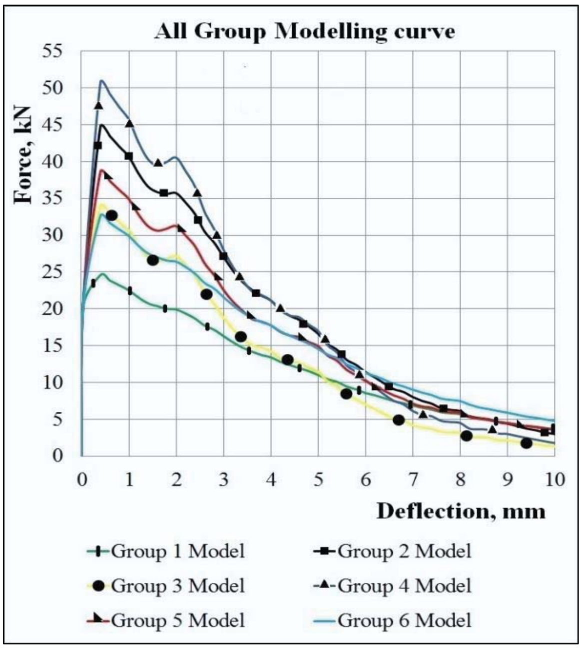

Fig. 5 Load - vertical deflection graphs for specimens modeling curve

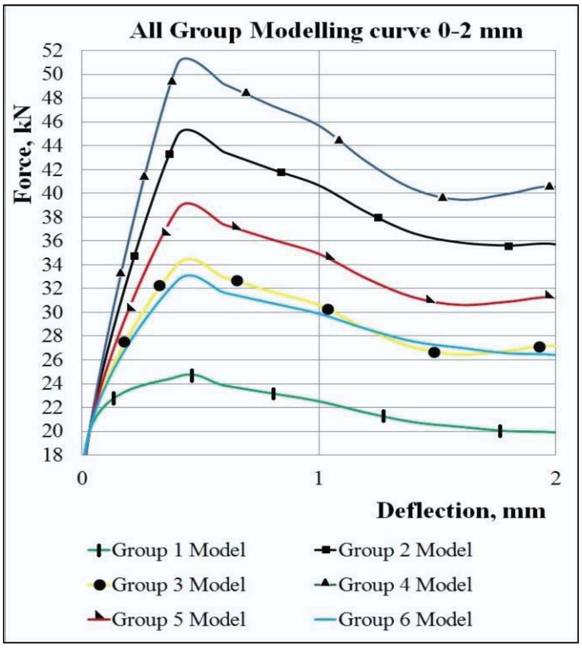

Fig. 6 Load - vertical deflection graphs for specimens modeling curve

The modeling results approximate the data obtained experimentally in the first and second stage of curves.

In the third stage the modeling results show a higher load carrying capacity for the specimens compared to obtained experimentally. The difference grows proportionally to the size of the crack opening. It can be explained by the homogenous distribution of fibers used in the model versus the non-homogenous in reality.

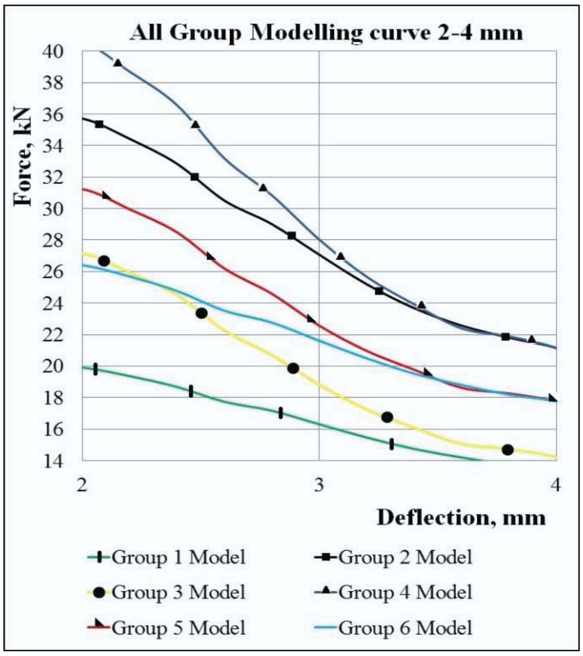

Fig. 7 Load - vertical deflection graphs for specimens modeling curve

V. Discussion and Summary

More important than the maximum force in SFRC strength analysis is the post-cracking behavior up on high strain levels. Higher fiber content allows transferring higher stresses at large crack openings. It is apparent that the post-cracking tensile strength immediately after cracking is increasing with growing fiber volume in layer sample.

As known from earlier research, experiments on laboratory-scale beam specimens confirmed a higher post-cracking strength when increasing fiber content sample layers [27], [28]. According to the test results, samples with non-homogeneous fiber distribution in the sample volume were showed a higher load carrying capacity. Explanation for this phenomenon may be such - they had higher fibers concentration were working under pull-out conditions, which was subjected to tensile loads [29].

The presented results indicate that growing fiber content has an increasing effect on the maximum force result.

The main contribution of steel fibres to concrete can mainly be observed after matrix cracking. If a proper design is made, after the matrix cracking, randomly distributed, short fibres in the matrix arrest microcracks, bridge these cracks, undergo a pull-out process and limit crack propagation [30], [31].

Debonding and pulling out the fibres require more energy, therefore, a substantial increase in toughness, and resistance to cyclic and dynamic loading occurs [32].

Although the same concrete mixture and volume fraction of fibers were used for the set of beams, the post-cracking behavior differed significantly. As expected the post cracking capacity became higher with increasing amount of fibres [27], [28]. The results were mainly influenced by the orientation and number of fibers acting at the crack section.

Experimental observation of fiber pull-out micromechanics [4] showed that the maximum load carrying capacity of fiber depends on the distribution of fiber towards direction of extraction force and how much the fiber has been extracted. Stage is characterized by the decline of total load carrying capacity of fiber. The capacity decreases proportionally to the size of crack opening. Load bearing - vertical deflection at the center of prism for the specimens of Groups 1, 2, 3, 4, 5 and 6 are given in Figs. 5-7.

Numerically, crack opening, under increasing applied load, was simulated using earlier elaborated model [25], [26], [33].

VI. Conclusion

According to the testing results, specimens with non-uniform (layered) fibers distribution in sample body were reached the highest load carrying capacity during crack opening stage.

Steel fibers can increase significantly the bending and the shear resistance of concrete structural element when steel fibers are working optimally.

Specimens showed typical tri-linear variation in their load–deflection, load–crack mouth opening and load–crack tip opening displacement curves under flexure.

The general conclusion for modeling results is that, the agreement with experimental data is good. The moderate disagreement in numerical values can have various reasons. Judging from modeling results presented in Figs. 5-7 the agreement with experimental data depends on fiber fraction in the mix. The possible reason for deviation from experimental data could also be because fiber orientation in layers contrary to modeling assumptions about random distribution across the volume and random distribution of orientation angles.

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Vitalijs Lusis was born in Riga, Latvia. He is a doctoral study student from 2011. In 2010 he received his professional Master Degree (M.sc.ing) in Civil Engineering at the Riga Technical University, Latvia. He graduated as a civil engineer and held a professional Bachelor degree in Civil Engineering (B.sc.ing) at the Riga Technical University in 2009.

He is lecturer of Faculty of Civil Engineering, Institute of Building production, Riga Technical University. Scientific work has been started in 2011. His research interests include fracture mechanics of fiber-reinforced concrete, durability of high performance concrete, extrusion technology, innovation fiber-reinforced concrete technologies.

V.Lusis is an author and co-author of 20 scientific publications, 9 patents for invention. Since 2011 he is member of Latvian Concrete Association and Latvian Materials Research Society.

Andrejs Krasnikovs was born in Krasnoyarsk, Russia. Has graduated Latvian State University in 1978, where he got Master Sc. degree in Physics. He joined the Institute of Polymer Mechanic of Latvian Academy of Sciences in 1978 and in 1986 he got Candidate of Sciences Degree (PhD) in Physics and Mathematics. Started at 1987 till the present time he is teaching and is performing research in Riga Technical University.

From 2006 he is professor in Institute of Mechanics, Faculty of Transport and Machine building. Simultaneously, started from 2000 he is a head of Concrete Mechanics laboratory at Civil Engineering Faculty. From 1992 he is a Doctor of Engineering Science (Dr.sc.ing.) and in 2011 he was elected as a Corresponding member of Latvian Academy of Sciences. A.Krasnikovs is an author and co-author of 160 scientific publications, 20 patents for invention and 3 educational books.

Dr.sc.ing, Professor, A.Krasnikovs is a member of ASME, ESCM, LNMC, LMRS and Concrete Association of Latvia, corresponding member of Latvian Academy of Sciences.